Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v41n1p112-118/2021

TECHNICAL PAPER

TECHNICAL AND ECONOMIC FEASIBILITY OF USING A VARIABLE-FREQUENCY DRIVE IN MICRO-IRRIGATION SYSTEMS

Marinaldo F. Pinto[1*], Diego J. de S. Pereira[2], Daniel F. de Carvalho[1],
Dinara G. Alves[1], Conan A. Salvador[1]

[1*]Corresponding author. Universidade Federal Rural do Rio de Janeiro - UFRRJ/ Seropédica - RJ, Brasil.
E-mail: marinaldo@ufrrj.br | ORCID: https://orcid.org/0000-0002-9368-6122

KEYWORDS

pumping system,
energy efficiency,
economic analysis.

ABSTRACT

Irrigation is essential for the development of crops in regions with scarcity or irregular rainfall distribution, enabling high productivity. However, the use of water resources and electrical energy leads to a concern with irrigation efficiency. Pressure demand varies during the operations of irrigation systems and the appropriate pressure can be regulated by variable-frequency drives for the power supply of the motor-pump set. This study aimed to analyze the technical and economic feasibility of using a variable-frequency drive to adjust the pressure in subunits of micro-irrigation systems. Laboratory tests were carried out to determine the electrical power consumed in each irrigated subunit for different slopes and the application or not of the variable-frequency drive. Thus, an economic analysis was carried out considering the electricity tariff for group B and rural consumer class, as well as different annual irrigation times. The results showed the potential for energy saving with the use of the variable-frequency drive. Thus, the economic analysis showed that the variable-frequency drive was a better alternative than the dissipative method.

INTRODUCTION

Pumping systems for irrigation are designed to work in the condition of maximum flow demand and total manometric head to meet all irrigation subunits (Lamaddalena & Khila, 2012; Khadra et al., 2016; Brar et al., 2017). However, some subunits require less power even at the time of maximum demand, and dissipative methods are commonly used to adjust the motor-pump operating point (Carvalho et al., 2000; Araújo et al., 2006).

Significant differences in power demand may occur between micro-irrigation subunits due to factors such as slope and/or length of different lateral and manifold, providing variable manometric heads to meet each subunit.

Pressure regulators and, in some cases, self-compensating emitters are required to adjust the pressure and flow in the subunits, allowing the pumping system to cover the entire area to be irrigated (Barreto Filho et al., 2000; Oliveira & Figueiredo, 2007). However, the use of these devices causes the dissipation of hydraulic energy, which reflects an increase in the consumption of electrical energy by the pumping system (Lamaddalena & Khila, 2013; Khadra et al., 2016).

Variable-frequency drives can provide better energy use efficiency in pumping systems, as the operation point of the motor-pump set is adjusted to the design point of each subunit by varying the motor supply frequency, acting on the control of its rotation (Araújo et al., 2006; Viholainen et al., 2013; Sungur et al., 2016; Valer et al., 2016). Thus, its use can provide an improvement in the pressure and flow control of irrigation systems, besides saving energy by avoiding the dissipation of hydraulic energy in pressure regulator devices (Burt et al., 2008).

Variable-frequency drives have been used in center pivot irrigation systems and the economic feasibility of using the equipment in these systems has been demonstrated

---

[1] Universidade Federal Rural do Rio de Janeiro - UFRRJ/ Seropédica - RJ , Brasil
[2] Escola Superior de Agricultura "Luiz de Queiroz" - ESALQ/USP/ Piracicaba - SP, Brasil

Area Editor: Edna Maria Bonfim-Silva
Received in: 3-7-2019
Accepted in: 10-22-2020

in several studies (Moraes et al., 2014; Lima et al., 2015; Brar et al., 2017). Micro-irrigation systems also present desirable characteristics for the use of this technology, and studies that focus on increasing energy efficiency are required, even if they are considered to have low power demand than other pressurized systems.

Thus, this study aimed to evaluate the technical and economic feasibility of using a variable-frequency drive to trigger the pump set in micro-irrigation systems.

SUBJECT DESCRIPTION

MATERIAL AND METHODS

This study was developed at the Laboratory of Hydraulics and Irrigation of the Department of Engineering, belonging to the Institute of Technology of the Federal Rural University of Rio de Janeiro (UFRRJ).

Manometric heads required for each micro-irrigation subunit were evaluated considering three slope conditions (0, 5, and 10%) in the direction of the longest terrain length and 0% in the direction of the shortest length. Two methods were considered to regulate pressure at the beginning of the manifold: the use of valves (dissipative method) and variable-frequency drives (non-dissipative method).

An experimental benchtop, composed of a motor-pump (Dancor, CAM series, standard 630, JM, 5CV), variable-frequency drive (WEG, CFW 10), pressure regulators, manometers, valves, electromagnetic flow meter (Krohne Conaut, OPTILUX KC 1000C/6 IFC 100C, with a measurement capacity of up to 10 $m^3 h^{-1}$), and emitters to provide the flow of the irrigation subunit, was set up.

The pressures at the outlet of the motor-pump set and the point corresponding to the start of the manifold were measured using the pressure transducer MSI 300-250-P-3-N. A digital multimeter (Minipa ET-3110) was used to acquire electrical variables (potential difference and current).

The following factors were considered to obtain the maximum area to be irrigated: highest yield flow of the motor-pump set (8 $m^3 h^{-1}$), net irrigation depth of 5 mm, and time available for irrigation of 16 h d^{-1}. An irrigation frequency of 1 day was adopted, thus allowing each subunit to be irrigated individually, according to the time of irrigation available. The area to be irrigated consisted of 2.3 ha under these conditions.

Thus, a rectangular area (210 × 110 m) was divided into 14 subunits of 55 × 30 m (Figure 1), providing lengths of the manifold of 28.5 m and the main line of 195 m. Each irrigation subunit was composed of 10 lateral lines spaced 3 m from each other, with a length of 54 m. Subunits located on the same terrain elevation (Figure 1) had the same pressure demand on the motor-pump set (1 and 14, 2 and 13, 3 and 12, 4 and 11, 5 and 10, 6 and 9, and 7 and 8).

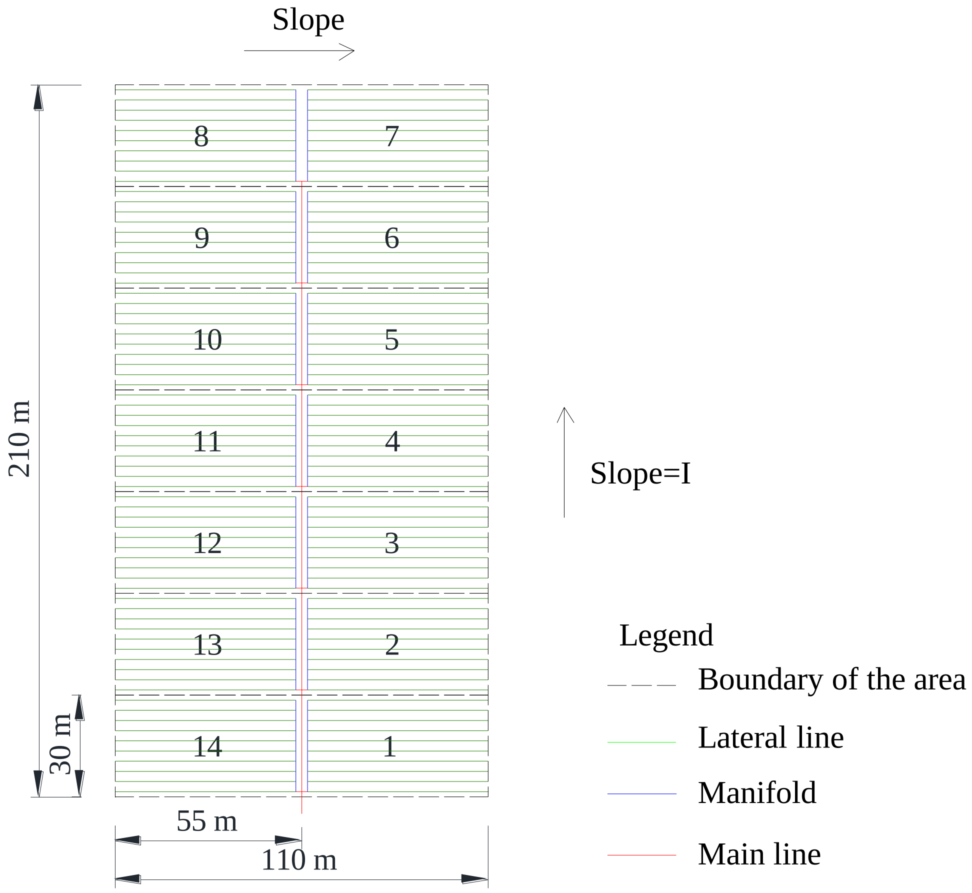

FIGURE 1. Scheme of the simulated area to be irrigated.

A dripper tube with integrated drippers with a flow of 4.3 L h^{-1} under a pressure load of 10 m, nominal diameter of 16 mm, spacing between emitters of 0.4 m, and flow regulation mechanism as a function of pressure (regulated emitter), whose exponent of the emitter flow-pressure equation tends to zero was considered for the hydraulic dimensioning of the lateral line. These emitter characteristics enabled to determine the maximum pressure variation allowed on the lateral line, which was assumed to be the operating pressure load range of the emitter (10 to 30 m), i.e., the maximum allowed variation was 20 m. This procedure was adopted because the allowed theoretical variation in regulated emitter tends to infinity [eq. (1)].

$$\Delta P = \left((1+q_{var})^{\frac{1}{x}} - 1\right) Ps;\ x \to 0;\ \Delta P \to \infty \quad (1)$$

Where:

ΔP is the pressure load variation in the subunit (m);

q_{var} is the allowable flow variation (dimensionless);

x is the exponent of the flow equation as a function of the emitter pressure (dimensionless), and

Ps is the emitter working pressure load (m).

The dimensioning of lateral line and manifold used eqs (2) to (5).

$$hf = \frac{0.00078 Q^{1.75} L\, F\lambda}{D^{4.75}} \quad (2)$$

$$F = \frac{1}{2.75} + \frac{1}{2N} + \frac{\sqrt{0.75}}{6N^2} \quad (3)$$

$$P_{inLL} = Ps + \frac{2.75}{3.75}\, hf_{LL} + \frac{\Delta Z}{2} \quad (4)$$

$$P_{inBL} = P_{inLL} + hf_{BL} + \frac{\Delta Z}{2} \quad (5)$$

Where:

hf is the pressure drop on the lateral line or manifold (m);

Q is the flow in the pipes (m^3 s^{-1});

L is the length of pipes (m);

F is the Christiansen's head loss reduction factor (dimensionless);

D is the pipe diameter (m);

N is the number of outlets on the lateral line or manifold (dimensionless);

λ is the local head loss factor (dimensionless);

ΔZ is the topographic gap (m);

Ps is emitter working pressure load (m);

P_{inLL} is the pressure load at the start of the lateral line (m), and

P_{inBL} is the pressure load at the start of the manifold (m).

The local head loss factor was determined according to Gomes et al. (2010) (Equations 6 to 9).

$$K = 1.387\ OI^{\,0.577} \quad (6)$$

$$OI = \left(\frac{At - Ag}{Ag}\right)^2 \quad (7)$$

$$L_{eq} = \frac{KD}{f} \quad (8)$$

$$\lambda = \frac{Se + L_{eq}}{Se} \quad (9)$$

Where:

OI is the obstruction index (dimensionless);

K is the local head loss coefficient (dimensionless);

At is the tube cross-section (m^2);

Ag is the internal dripper cross-section (m^2);

f is the friction factor (dimensionless);

Se is the spacing between emitters (m), and

Leq is the equivalent length (m).

The data of the length of the lateral line of 54 m, the flow of 0.5805 m^3 h^{-1}, the internal diameter of 13.8 mm, and local head loss factor of 1.99 allowed obtaining a head loss of 4.86 m, which is within the limit that would be half the pressure variation in the subunit, corresponding to 10 m. The pressure required at the start of the lateral line was 13.6 m. Nominal diameter of 32 mm was adopted for the manifold, whose internal diameter is 28.4 mm, flow rate of 5.805 m^3 h^{-1}, length of 28.5 m, head loss factor of 1.32, obtaining a head loss of 3.26 m and meeting the criteria established for the dimensioning.

The velocity criterion (Equation 10) was used for the dimensioning of the main line piping, in which the lower and upper limits were 1.0 and 2.5 m s^{-1}, with a nominal diameter of 40 mm, whose internal diameter is 36.2 mm. The flow considered was 5.805 m^3 h^{-1}, corresponding to the flow of the manifold (irrigation of one subunit at a time), providing a speed of 1.57 m s^{-1}. The head loss was determined using [eq. (11)], being calculated for each subunit, and considering its distance to the control station.

$$v = \frac{4Q}{\pi D^2} \quad (10)$$

$$hf_{ML} = \frac{0.00078 Q^{1.75} L}{D^{4.75}} \quad (11)$$

Where:

v is the flow velocity (m s^{-1}), and

hf_{ML} is the head loss on the main line (m).

The manometric head required in each subunit was determined from the head loss at the control station and pump suction of 2.9 m, a variable topographic gap depending on the subunit in operation and the slope of the evaluated soil, and a variable head loss on the main line depending on the distance from the subunit to the pump (Equation 12).

$$Hm = P_{inLD} + hf_{LP} + hf_{CC} + hf_s + \Delta Z \quad (12)$$

Where:

hf_{CC} is the head loss at the control station (m);

hf_S is the pressure drop at the pump suction (m);

ΔZ is the topographic gap (m), and

Hm is the manometric head (m).

The pressure in each subunit was adjusted by partial closing of the gate valve (energy dissipative method) in tests without the use of the variable-frequency drive. On the other hand, the adjustment in tests using the variable-frequency drive was performed by controlling the motor supply frequency for each subunit. The simulation of the head loss on the main line and topographic gap was carried out by partially closing a gate valve installed in the discharge pipe, according to the procedure adopted by Moraes et al. (2014). Table 1 shows the values of manometric head required in each subunit for slopes of 0, 5, and 10%.

TABLE 1. Pressure values in each subunit for slopes of 0, 5, and 10%.

Subunit	Slope (%)		
	0	5	10
	Manometric head (m)		
1 and 14	20.59	21.94	23.29
2 and 13	21.91	24.76	27.61
3 and 12	23.22	27.57	31.92
4 and 11	24.54	30.39	36.24
5 and 10	25.86	33.21	40.56
6 and 9	27.17	36.02	44.87
7 and 8	28.49	38.84	49.19

The electrical power demanded by the motor in the different scenarios was determined by measuring the current and potential difference, using a digital multimeter (Equation 13). The power factor was obtained from the engine manufacturer’s manual, considering the engine load in each evaluated situation.

$$\mathrm{Po} = \frac{\sqrt{3} \times \mathrm{V} \times \mathrm{I} \times \cos\alpha}{1000} \tag{13}$$

Where:

Po is the consumed power (kW);

V is the potential difference of the electrical grid (V);

I is the electric current (A), and

cos α is the power factor (dimensionless).

The evaluated alternatives were compared from the total annual cost (Equation 14), considering the sum of the energy cost and the investment cost with the variable-frequency drive (R$ 1,500.00) or valves (R$ 3,806.18 for the 14 valves) in current monetary values.

$$\mathrm{TAC} = \mathrm{I}\ \frac{(1+\mathrm{i})^{\mathrm{n}}\,\mathrm{i}}{(1+\mathrm{i})^{\mathrm{n}}-1} + \mathrm{C} \times \mathrm{Po} \times \mathrm{time} \tag{14}$$

Where:

TAC is the total annual cost (R$), i is the annual interest rate (dimensionless);

n is the equipment useful life (years);

I is the initial investment (R$);

C is the electricity consumption tariff (R$ kWh^{-1}), and

time is the annual irrigation time (h).

The useful life of the equipment was considered to be 10 years, annual irrigation time of 500, 1000, 1500, and 2000 h, and annual interest rate (Selic interest rate) of 12.53% per year, corresponding to the average of the 229th and 230th meeting of the Central Bank of Brazil’s Monetary Policy Committee (COPOM) (2017). The electric tariff for group B (low voltage) and rural consumer class was adopted, with monthly consumption above 300 kWh (R$ 0.51214 kWh^{-1}), according to LIGHT (2017).

The classification in the rural class is due to the objectives of the study. Consumers of this category may be benefited from discounts in tariffs in case of practicing irrigation at night (Sá Júnior & Carvalho, 2016) although the price differentiation by time of use is not evaluated in this study.

RESULTS AND DISCUSSION

The electrical power demanded in each subunit for the 0, 5, and 10% slope conditions, with and without variable-frequency drive, is shown in Figure 2. In general, the power demanded in each subunit is directly proportional to the pressure required in the motor-pump set, with the lowest and highest power observed in subunits 1 and 7, respectively.

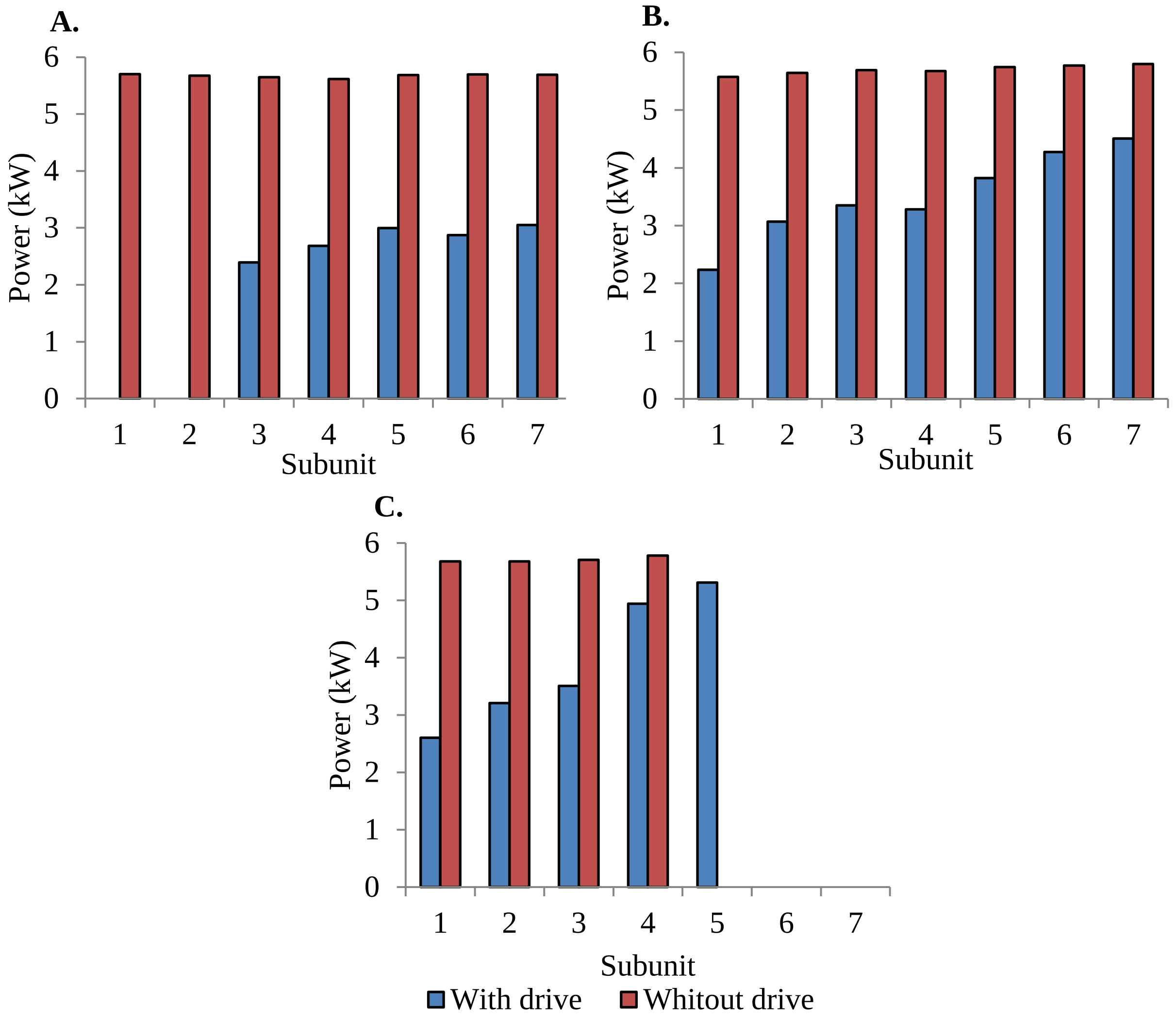

FIGURE 2. Power demanded in each subunit with and without the use of the variable-frequency drive: A. 0% slope; B. 5% slope; and C. 10% slope.

The power required in the different slope conditions and between subunits were similar by the dissipative method (Figure 2), considering that the manometric head was maintained practically constant to allow the pump operating point to be also maintained at the project point. The manometric head was adjusted by controlling the partial closing of the gate valve, as the pressure demand in each subunit is different.

The comparison between the slope and scenarios with and without the use of the variable-frequency drive showed a decrease in the demanded power when it was used. The demanded power for the 0% slope showed no significant increases along the subunits due to the small difference in manometric head required by the pumping system (Figure 2). However, the power required in the more distant subunits also increased as the slope increased. It demonstrates that the higher the slope, the higher the potential for energy savings when using the variable-frequency drive, as found by Moraes et al. (2014) in a center pivot prototype controlled through the variable-frequency drive.

The difference between powers demanded with and without using the variable-frequency drive decreased as the subunits distanced from the motor-pump set under the 5 and 10% slope conditions (Figure 2B and 2C, respectively), that is, a higher possibility of reducing energy consumption occurs in subunits closest to the motor-pump set.

The potential savings under the 0% slope condition ranged from 46 to 58%, with the lowest value in the most distant subunit. The 5% slope condition presented savings of 60% in subunit 1 and 22% in subunit 7. The 10% slope showed values between 54 and 8% of electrical power reduction.

The analysis of the area of the hydraulic project showed that the variable-frequency drive promoted a reduction in the demanded power of 51, 39, and 38% for the 0, 5, and 10% slope, respectively. Moraes et al. (2014) evaluated slopes of 0, 10, 20, and 30% for a center pivot and observed energy savings of 48, 37, 26, and 16%, respectively, demonstrating the importance of this factor in energy savings. Córcoles et al. (2019) evaluated the feasibility of using variable-frequency drives to capture water from wells for irrigation and found energy savings ranging from 6.8 to 23%, depending on the characteristics of the irrigated areas and the dynamic variations of the water depth in the well. Araújo et al. (2006) obtained a power reduction of around 30% when using a variable-frequency drive in a conventional sprinkler system, considering the number of lateral lines in simultaneous operation.

The fact that the 0% slope scenario has promoted the highest reductions in consumption when the variable-frequency drive is used must be analyzed with caution because this result may vary depending on the power of the motor-pump set. In cases in which the motor-pump set is oversized, as is the analyzed case, the slope does not affect the pumping costs when the drive is not used because excess pressure is dissipated in the form of pressure loss in the control valve, increasing the power that can be saved using the variable-frequency drive.

Ferreira et al. (2008) analyzed energy efficiency in pumping systems and found that the potential for electricity savings when using a variable-frequency drive instead of the dissipative method depends on the proximity of the project point to the motor-pump operation point.

Figure 3 shows the total annual costs under the conditions with and without the variable-frequency drive, terrain slopes of 0, 5, and 10%, and annual irrigation time of 500, 1000, 1500, 2000 h. The total annual cost is higher when no variable-frequency drive is used, regardless of the annual irrigation time. It occurs because the initial investment for the acquisition of valves is higher than for the acquisition of the variable-frequency drive, the latter still providing a reduction in the cost related to energy consumption.

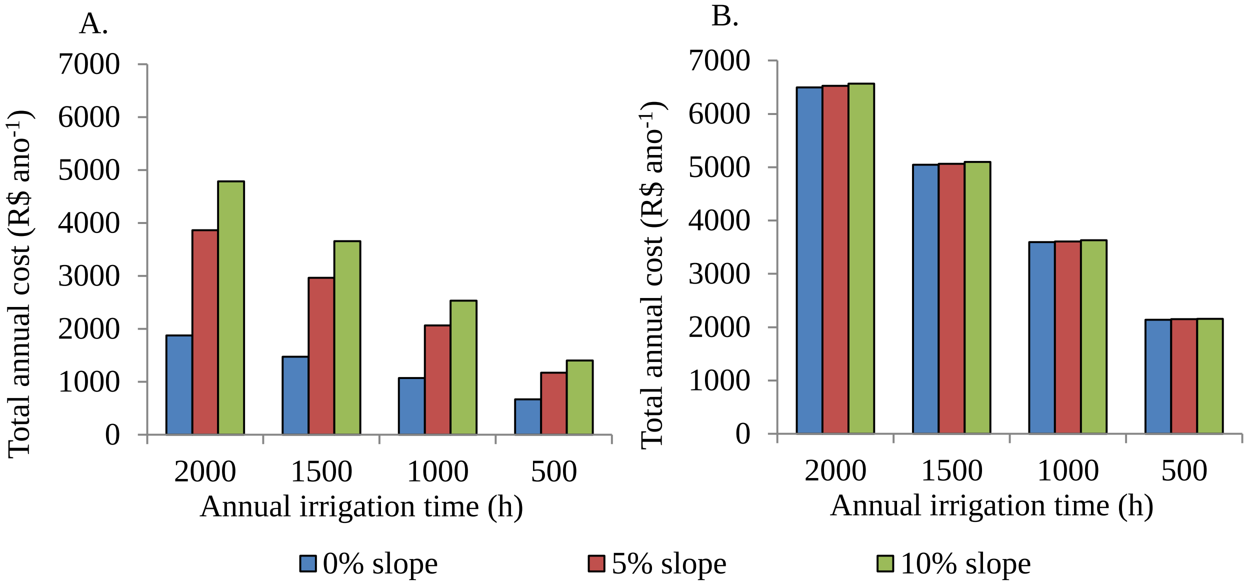

FIGURE 3. Total annual cost for different slopes and irrigation times. A. With the variable-frequency drive; and B. Without the variable-frequency drive.

The annual irrigation time was decisive for the feasibility of the use of the variable-frequency drives in other irrigation systems (Carvalho et al., 2000; Araújo et al., 2006; Córcoles et al., 2019). Araújo et al. (2006) found the leveling point between the number of hours worked and the economic feasibility of variable-frequency drives in center pivot motor-pump sets, considering various powers of drives associated with different working pressures. Córcoles et al. (2019) pointed out that the economic feasibility of this equipment depends on several factors such as energy savings, drive cost, and applied water depths.

Carvalho et al. (2000) evaluated the feasibility of using variable-frequency drives to control the flow in irrigation systems and concluded that the decisive variables were the annual irrigation time and the demanded power reduction. However, the authors did not consider the reduction in costs related to the components of irrigation systems because it was a generic analysis. Pressure-regulating valves in the micro-irrigation represented the largest portion of the initial cost in the economic analysis.

The use of the variable-frequency drive promoted cost reduction under all the analyzed situations compared to the energy dissipative method, being higher for the 0% slope. An annual cost reduction of R$ 7,532.23 and R$ 2,088.68 was obtained for annual irrigation times of 2000 and 500 h, respectively, under this condition. In percentage terms, savings reached 71.43, 40.33, and 26.28% for the 0, 5, and 10% slope scenarios.

CONCLUSIONS

1. The use of the variable-frequency drive was technically feasible for adjusting the hydraulic power in the subunits of the micro-irrigation system, presenting the same technical performance as the energy dissipative method.
2. The use of the variable-frequency drive was the best economical alternative for all the evaluated conditions of relief and annual irrigation times.

ACKNOWLEDGMENTS

To the Paraíba do Sul River Basin Agency (AGEVAP) for financing this research (grant No. 025/2016).

REFERENCES

Araújo JAB, Seraphim OJ, Siqueira, JAC, Presenço F, Caneppele FL (2006) Avaliação de um sistema irrigação por aspersão com aplicação do inversor de frequência no conjunto motobomba. Irriga 11(3):319-327.

Banco Central do Brasil. Histórico da Taxa de juros. Available: https://www.bcb.gov.br/Pec/Copom/Port/taxaSelic.asp. Acessed Mar 8, 2017.

Barreto Filho AA, Dantas Neto J, Matos JA, Gomes EM (2000) Desempenho de um sistema de irrigação por microaspersão, instalado a nível de campo. Revista Brasileira de Engenharia Agrícola e Ambiental 4(3):309-314.

Brar D, Kranz, WL, Lo TH, Irmak S, Martin DL (2017) Energy conservation using variable-frequency drives for center-pivot irrigation: standard systems. American Society of Agricultural and Biological Engineers 60(1):95-106. DOI: http://dx.doi.org/ 10.13031/trans.11683

Burt CM, Piao X, Gaudi F, Busch B, Taufik NFN (2008) Electric Motor Efficiency under Variable Frequencies and Loads. Journal Of Irrigation And Drainage 134(2):129-136. DOI: http://dx.doi.org/10.1061/(ASCE)0733-9437(2008)134:2(129)

Carvalho JA, Mello CR, Braga Júnior RA, Reinato CHR, Santana MJ (2000) Utilização do inversor de frequência em sistemas de irrigação para controle de vazão. Revista Brasileira de Engenharia Agrícola e Ambiental 36(1):51-56.

Córcoles JI, Perea RG, Izquiel I, Moreno MA (2019) Decision support system tool to reduce the energy consumption of water abstraction from aquifers for irrigation. Water 11 (323):1-19. DOI: http://dx.doi.org/ 10.3390/w11020323

Ferreira RA, Silva SFP, Delaiba AC, Bispo D (2008) Metodologia de eficiência energética aplicada em sistemas de bombeamento. Eletrônica de Potência 13(4):251-257.

Gomes AW, Frizzone JA, Rettore Neto O, Miranda JH (2010) Perda de carga localizada em gotejadores integrados em tubos de polietileno. Engenharia Agrícola 30(3):435-446.

Khadra R, Moreno MA, Awada H, Lamaddalena N (2016) Energy and hydraulic performance based management of large-lcale pressurized irrigation systems. Water Resources Management 30:3493-3506.

Lamaddalena N, Khila S (2012) Energy saving with variable speed pumps in on-demand irrigation systems. Irrigation Science 30(2):157–166. DOI: https://doi.org/10.1007/s00271-011-0271-7

Lamaddalena N, Khila S (2013) Efficiency-driven pumping station regulation in on-demand irrigation systems. Irrigation Science 31(3):395-410. DOI: https://doi.org/10.1007/s00271-011-0314-0

Light - Light Serviços de Eletricidade S.A. Composição da tarifa. Available: http://www.light.com.br/para-residencias/Sua-Conta/composicao-da-tarifa.aspx. Acessed Mar 8, 2017.

Lima AS, Zoocler JL, Jadoski SO, Maggi MF, Amarante RR (2015) Desempenho operacional no bombeamento em pivô central utilizando inversor de frequência. Brazilian Journal of Applied Technology for Agricultural Science 8(2):51-61. DOI: https://doi.org/10.5935/PAeT.V8.N2.06

Moraes MJ, Oliveira Filho D, Mantovani EC, Monteiro PMB, Mendes ALC, Damião JHAC (2014) Automação em sistema de irrigação tipo pivô central para economia de energia elétrica. Engenharia Agrícola 34(6):1075-1088.

Oliveira FG, Figueiredo FP (2007) Influência do espaçamento entre aspersores e do uso de válvulas reguladoras de pressão na uniformidade de irrigação por aspersão convencional. Ceres 54(316):506-510.

Sá Júnior A, Carvalho JA (2016) Análise comparativa do custo para aplicação de uma lâmina de irrigação utilizando energia elétrica e diesel. Revista Energia na Agricultura 31(3)259-266. DOI: http://dx.doi.org/10.17224/EnergAgric.2016v31n3p259-266

Sungur C, Çalişir S, Kaya E (2016) Developing an automation system for improving the energy efficiency of constant pressure irrigation pumps. Journal of Irrigation and Drenage 142(11): 1-7. DOI: https://doi.org/ 10.1061/(ASCE)IR.1943-4774.0001046

Valer R, Melendez TA, Fedrizzi MC, Zilles R, Moraes AM (2016) Variable-speed drives in photovoltaic pumping systems for irrigation in BrazilL. Sustainable Energy Technologies and Assessments 15(3): 20-26. DOI: https://dx.doi.org/ 10.1016/j.seta.2016.03.003

Viholainen J, Tamminen J, Ahonen T, Ahola J, Vakkilainen E, Soukka R (2013) Energy-efficient control strategy for variable speed-driven parallel pumping systems. Energy Efficiency 6(3):495–509. DOI: https://doi.org/10.1007/s12053-012-9188-0